Testing Mass Varying Neutrino With Short Gamma Ray Burst

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In this paper we study the possibility of probing for the absolute neutrino mass and its variation with short Gamma Ray Burst (GRB). We have calculated the flight time difference between a massive neutrino and a photon in two different approaches to mass varying neutrinos. Firstly we parametrize the neutrino mass as a function of redshift in a model independent way, then we consider two specific models where the neutrino mass varies during the evolution of the Quintessence fields. Our calculations show in general the value of the time delay is changed substantially relative to a constant neutrino mass. Furthermore our numerical results show that the flight time delay in these models is expected to be larger than the duration time of the short GRB, which opens a possibility of testing the scenario of mass varying neutrino with the short GRB.

In the recent years astronomical observations show that the Universe is spatially accelerating at the present time[1]. The simplest account of this cosmic acceleration seems to be a remnant small cosmological constant, but it suffers from the difficulties associated with the fine tuning and coincidence problem, so many physicists are attracted with the idea that the acceleration is driven by dynamical scalar fields, such as Quintessence. In models of dark energy with a remnant small cosmological constant or (true or false) vacuum energy $\rho \sim (2\times 10^{-3}\text{ev})^4$. This energy scale $\sim 10^{-3}$ ev is smaller than the energy scales in particle physics, but interestingly is comparable to the neutrino masses. This indicates a possible connection between the neutrinos and the dark energy. Furthermore, in Quintessence-like models $m_Q \sim 10^{-33}$ eV, which surprisingly is also connected to the neutrino masses *via* a see-saw formula $m_Q \sim m_\nu^2/M_{pl}$ with M_{pl} the planck mass.

Is there really any connections between the neutrinos and dark energy? Given the arguments above it is quite interesting to make such a speculation on this connection. If yes, however in terms of the language of the particle physics it requires the existence of new dynamics and new interactions between the neutrino and the dark energy sector. Recently there are some studies in the literature on the possible realization of the models on neutrinos and dark energy[2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. One of the interesting predictions of these models[12] is that neutrino masses are not constant, but vary as a function of time during the evolution of the universe. In this paper we study the possibility of testing this scenario of mass varying neutrinos with the gamma ray burst.

There are strong evidences for the non-vanishing neutrino masses from the neutrino oscillation experiments, however the neutrino masses given by the solar neutrinos and atmosphere neutrinos experiments are not the absolute values, but mass square difference: $\Delta m^2_{\odot} \sim 8\times 10^{-5}eV^2$(solar neutrino experiment), $\Delta m^2_{atm} \sim 2\times 10^{-3}eV^2$(atmosphere neutrino experiment)[13]. The cosmological observations for example Wilkinson Microwave Anisotropy Probe(WMAP) and Sloan Digital Sky Survey(SDSS) provide a limit on the absolute value of the neutrino mass which for a degenerated spectrum corresponds to $m = 0.6$ eV[14]. Studying the time delay of neutrinos from the GRB serves another way to measure the absolute value of the neutrino masses[15, 16].

As it is known that most of the energy of a supernova is released in the form of neutrinos, and therefore it is widely expected that GRBs are similarly regarded as a high intensity, high energy neutrino beam with a cosmological baseline which may be detected in future neutrino telescopes[15, 17, 18, 19, 20, 21].

The time delay t_d is defined as the time difference between a massive neutrino and a photon emitted from a given source,

$$t_d \approx \int_t^{t_0} a(t')dt' \frac{1}{2}\frac{m^2}{p^2}, \tag{1}$$

where p is the neutrino energy measured at the detector, m is the neutrino mass, and $a(t)$ is the expansion factor of the universe which by normalization is set to be $a(t_0) = 1$ at present time t_0. One can see that the integration over t from the time of emission of the photon and neutrino to the present("t_0") contains information on the cosmology and depends on the cosmological parameters. With the results of the cosmological parameters given by the recent WMAP and SDSS group, $\Omega_{\Lambda_0} = 0.73$ and $\Omega_{m_0} = 0.27$, we have that:

$$t_d \approx \frac{1}{2}\frac{m^2}{p^2}\int_0^Z \frac{dz'}{(1+z')^2 H_0\sqrt{\Omega_{\Lambda_0} + (1+z')^3\Omega_{m_0}}}. \tag{2}$$

In the numerical calculation we will take the Hubble constant $H_0 = 1.5359\times 10^{-42}$ GeV. In Fig.1 we plot t_d as a function of p the neutrino energy for four different values of the redshifts. And to get the possible maximal value of the time delay t_d, in the numerical calculation we have taken the degenerated neutrino mass pattern and the current cosmological upper limit $m < 0.6$eV. By measuring

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the t_d one would be able to determine the absolute value of the neutrino mass, however in general since the photons are trapped inside the fireball and are released much later, the neutrino and the photon will not be emitted at the same time. This will add an systematic error in the measurement of the t_d, consequently an uncertainty in the determination of the neutrino masses. To reduce this type of systematic error we focus on the short GRB whose duration is generally less than 2 seconds or even much shorter, For example Burst And Transient Source Experiment(BATSE) has discovered a GRB with duration only 5 milliseconds[22]. It has been widely argued that short GRBs are produced by the merger of two compact objects (e.g., neutron stars or black holes)[23], and that their environments are likely to be low-density media because the merging place is far away from the birth site of one neutron star. Even so, the predicted afterglows from short GRBs appear to be detectable with current instruments in the Swift era[24]. Once such afterglows are detected, the redshifts of short GRBs may be measured.

From Fig. 1 one can see that in general the time delay t_d is longer than the duration of the short GRB. For example for $m = 0.6$ eV, $z = 2, p = 10$Mev, t_d is around 400 seconds; especially for the $GRB030329$ with redshift $z = 0.17$, t_d is 112 seconds. The time delay for these cases is expected to be detectable in principle. If not, this will put a limit on the absolute value of the neutrino mass better than the cosmological limits.

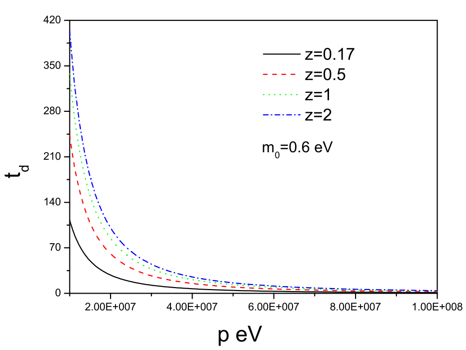

FIG. 1: t_d (unit in second) as a function of p for different redshifts z=0.17(solid), 0.5(dashed), 1(dotted), 2(dash dotted).

In the following we will discuss the possibility of testing on the variation of the neutrino masses with the short GRB. First of all we parametrize the variation of the neutrino mass in a model independent way, then we will take two concrete models of Quintessence for the calculation of mass variation and the time delay of the neutrinos. Consider a general case where m_ν is an arbitrary function of the redshift Z, $i.e. m(Z)$, one can expand it in terms of redshift z. For small z, we get:

$$m(Z) = m_0 + m'Z + \frac{1}{2}m''Z^2 + ...$$

$$= m_0(1 + \frac{m'(0)}{m_0}Z + ...). \quad (3)$$

Defining $c \equiv \frac{m'(0)}{m_0}$, we have

$$m = m_0(1 + cZ + ...), \quad (4)$$

where m_0 is the neutrino mass at $z = 0$. Replacing the neutrino mass in (1) by (5) we obtain that

$$t_d \approx \frac{1}{2}\frac{m_0^2}{p^2}\int_0^Z \frac{(1 + cz')^2 dz'}{(1 + z')^2 H_0 \sqrt{\Omega_{\Lambda_0} + (1 + z')^3 \Omega_{m_0}}}. \quad (5)$$

In Fig. 2 we plot t_d as a function of $\frac{m_0}{p}$. Note that here the neutrino mass in (5) varies as a function of redshift z. From Fig. 2 one can see that the variation of the

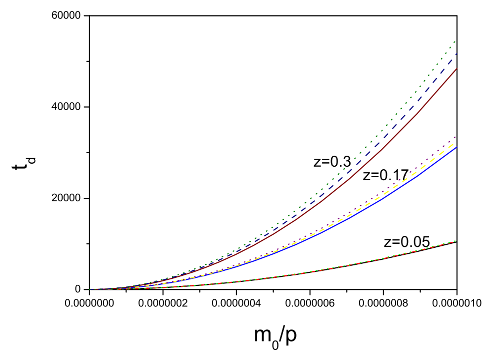

FIG. 2: t_d (unit in second) as a function of $\frac{m_0}{p}$ for different coefficient c: c=0(solid), 0.5(dashed), 1(dotted).

neutrino mass does change the value of t_d compared to that if the neutrino mass is constant ($c = 0$).

The neutrino mass in the standard model of electroweak theory comes from a dimension five operator

$$\mathcal{L} = \frac{2}{f}\nu\nu\phi\phi + h.c., \quad (6)$$

and $m_\nu \sim \frac{v^2}{f}$ where f is the scale of the new physics generating the neutrino mass and v is the vacuum expectation value of the Higgs fields. In order to have a mass varying neutrino we introduce a coupling of Quintessence to the neutrinos,

$$\beta\frac{Q}{M_{pl}}\frac{2}{f}\nu\nu\phi\phi + h.c., \quad (7)$$

where β is the coefficient which characterizes the strength of Quintessence interacting with the neutrinos and generally one requires $\beta < 4\pi$ to make the effective lagrangian description reliable.

Combining (8) with (7) the neutrino mass is given by:

$$m = m_0\frac{1}{1 + \beta\frac{Q_0}{M_{pl}}}(1 + \beta\frac{Q}{M_{pl}}), \quad (8)$$

where m_0 and Q_0 are the neutrino mass and the value of Quintessence at present time, and M_{pl} is the Plank scale.

Now the formula for the time-delay is given by

$$t_d = \frac{1}{2}(\frac{m_0}{p})^2 \frac{1}{(1+\beta\frac{Q_0}{M_{pl}})^2} \int_t^{t_0} (1+\beta\frac{Q}{M_{pl}})^2 a(t')dt'. \quad (9)$$

To evaluate t_d we need to know the evolution of the Quintessence which can be obtained by solving the following equations of motion of the Quintessence. For a flat Universe they are,

$$H^2 = \frac{8\pi G}{3}(\rho_B + \frac{\dot{Q}^2}{2} + V(Q)), \quad (10)$$

$$\ddot{Q} + 3H\dot{Q} + V'(Q) = 0, \quad (11)$$

$$\dot{H} = -4\pi G((1+\omega_B)\rho_B + \dot{Q}^2), \quad (12)$$

where ρ_B and ω_B represent the energy density and the equation-of-state of the background fluid respectively, for example $\omega_B = \frac{1}{3}$ in radiation-dominated and $\omega_B = 0$ in the matter-dominated Universe.

For a numerical study, we consider a model of Quintessence with a inverse power-law potential[25],

$$V = V_0 Q^{-\alpha}. \quad (13)$$

This type of model is shown[25, 26] to have the property of tracking behavior. In the calculation we take $\alpha = 0.5$ which gives rise to $\omega_{Q_0} < -0.78$ constrained by the WMAP. In Fig. 3 we plot the numerical value of t_d . From Fig. 3 one can see the time delay t_d is enhanced substantially relative to a constant value of the neutrino mass. For example, if $(\frac{m_0}{p})^2 \sim 10^{-7}$, and $\beta = -3$, t_d can reach 1624 seconds at $z = 3$. For comparison a constant neutrino mass $\beta = 0$ reduces t_d to 1075 seconds.

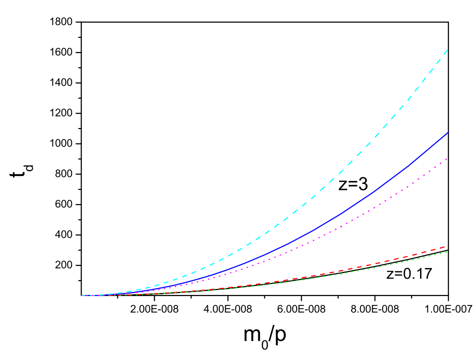

FIG. 3: Plot of t_d (unit in second) as a function of $\frac{m_0}{p}$. The three curves correspond to parameter β=0(solid), -3(dash), 3(dot) respectively for a given redshift.

For the case of hierarchical neutrino mass patter, the heavy neutrino mass set by the atmosphare neutrino oscillation is $m \sim 0.05$eV. With this value one can see from Fig.3 that t_d is only 0.5 seconds for the constant-mass neutrinos with energy $p = 12$ Mev and redshift $z = 3$. This value is much smaller than the short GRB duration and will be difficult to be observable. If the neutrino mass varies, as shown in Fig. 3 t_d will be enhanced substantially. Numerically Fig.3 shows that t_d can be increased to 3 seconds.

Certainly the results shown in Fig.3 depends on the Quintessence model. For an illustration , we consider another Quintessence model

$$V = V_0 exp(\frac{\lambda}{Q}). \quad (14)$$

In this calculation we take $\lambda = 0.5M_{pl}$. From Fig.4 one can see that different model of Quintessence does give a different result of t_d, but the t_d is in general larger than the duration time of the short GRB.

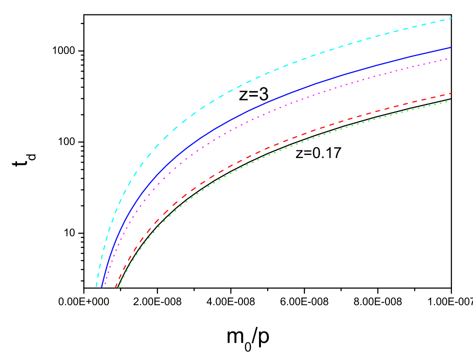

FIG. 4: Plot of t_d (unit in second) as a function of $\frac{m_0}{p}$. The three curves correspond to parameters β=0(solid), -2(dash), 10(dot) respectively for a given redshift.

In summary we have in this paper discussed the possibility of using the Short GRB to probe for the absolute neutrino masses and its variation. By a detailed calculation we have shown that with the current cosmological limits on the degenerated neutrino masses the time delay t_d will be in general longer than the time of the duration, furthermore the changes to the t_d caused by the variation of the neutrino masses are also expected to be larger than the time of the duration. Our results indicate the possibility of testing the scenario of mass varying neutrino in the future neutrino telescope.

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